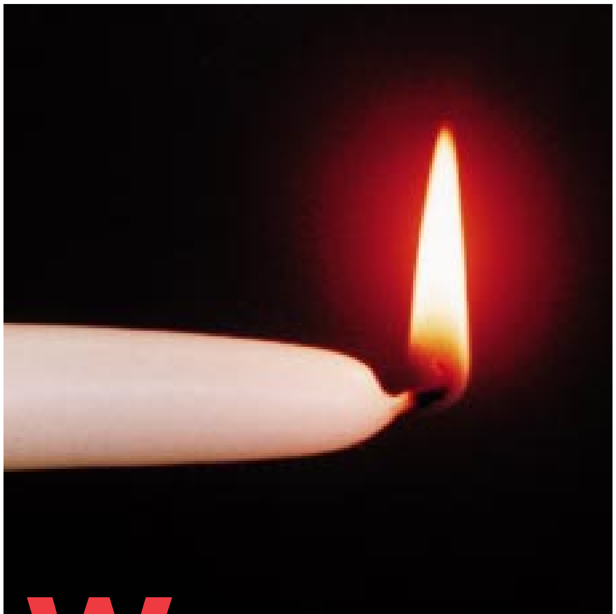
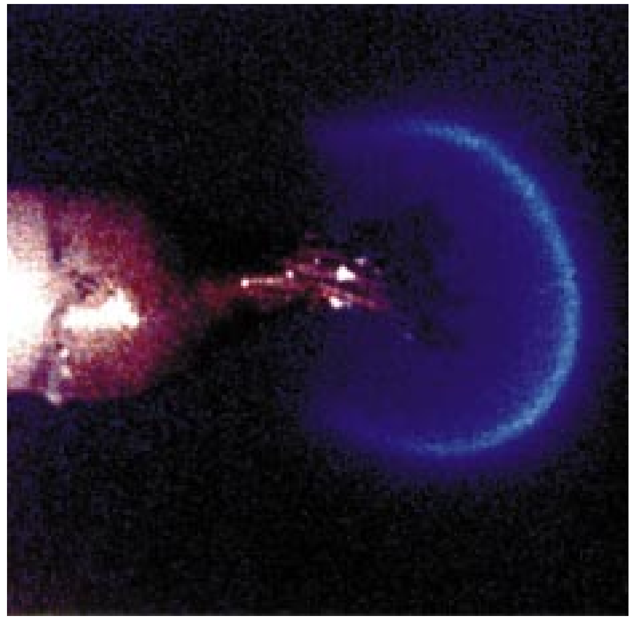
MICROGRAVITY RESEARCH DIVISION

Combustion Science





What Is Combustion Science?

Combustion, or burning, is a rapid, self-sustaining chemical reaction that releases a significant amount of heat. Examples of common combustion processes are burning candles, forest fires, log fires, the burning of natural gas in home furnaces, and the burning of gasoline in internal combustion engines. For combustion to occur, three things must normally be present: a fuel, an oxidizer, and an ignition stimulus. (An exception is hypergolic combustion, in which a fuel and an oxidizer spontaneously react on contact without the need for an ignition stimulus.) Fuels can be solid, liquid, or gas. Examples of solid fuels include filter paper, wood, and coal. Liquid fuels include gasoline and kerosene. Propane and hydrogen are examples of gaseous fuels. Oxidizers can also be solid (such as ammonium perchlorate, which is used in space shuttle booster rockets), liquid (like hydrogen peroxide), or gaseous (like oxygen). Air, which contains oxygen, is a particularly common oxidizer. An electrical spark is an example of an ignition stimulus.

Combustion is a key element of many of modern society's critical technologies. Electric power production, home heating, ground transportation, spacecraft and aircraft propulsion, and materials processing all use combustion to convert chemical energy to thermal energy or propulsive force. Although combustion, which accounts for approximately 85 percent of the world's energy usage, is vital to our current way of life, it poses great challenges to maintaining a healthy environment. Improved understanding of combustion will help us deal better with the problems of pollutants, atmospheric change and global warming, unwanted fires and explosions, and the incineration of hazardous wastes. Despite vigorous scientific examination for over a century, researchers still lack full understanding of many fundamental combustion processes.

The objectives of NASA's microgravity combustion science program are to enhance our understanding of the fundamental combustion phenomena that are affected by gravity, to use research results to advance combustion science and technology on Earth, and to address issues of fire safety in space. The program, which operates under the direction of the Microgravity Research Division, combines the results of experiments conducted in both ground-based low-gravity facilities and space facilities and supports research in how flames ignite, spread, and extinguish under microgravity conditions. (See back page for more information about microgravity, or µg.)

Lewis Research Center in Cleveland, Ohio, is the Microgravity Center of Excellence for combustion science.

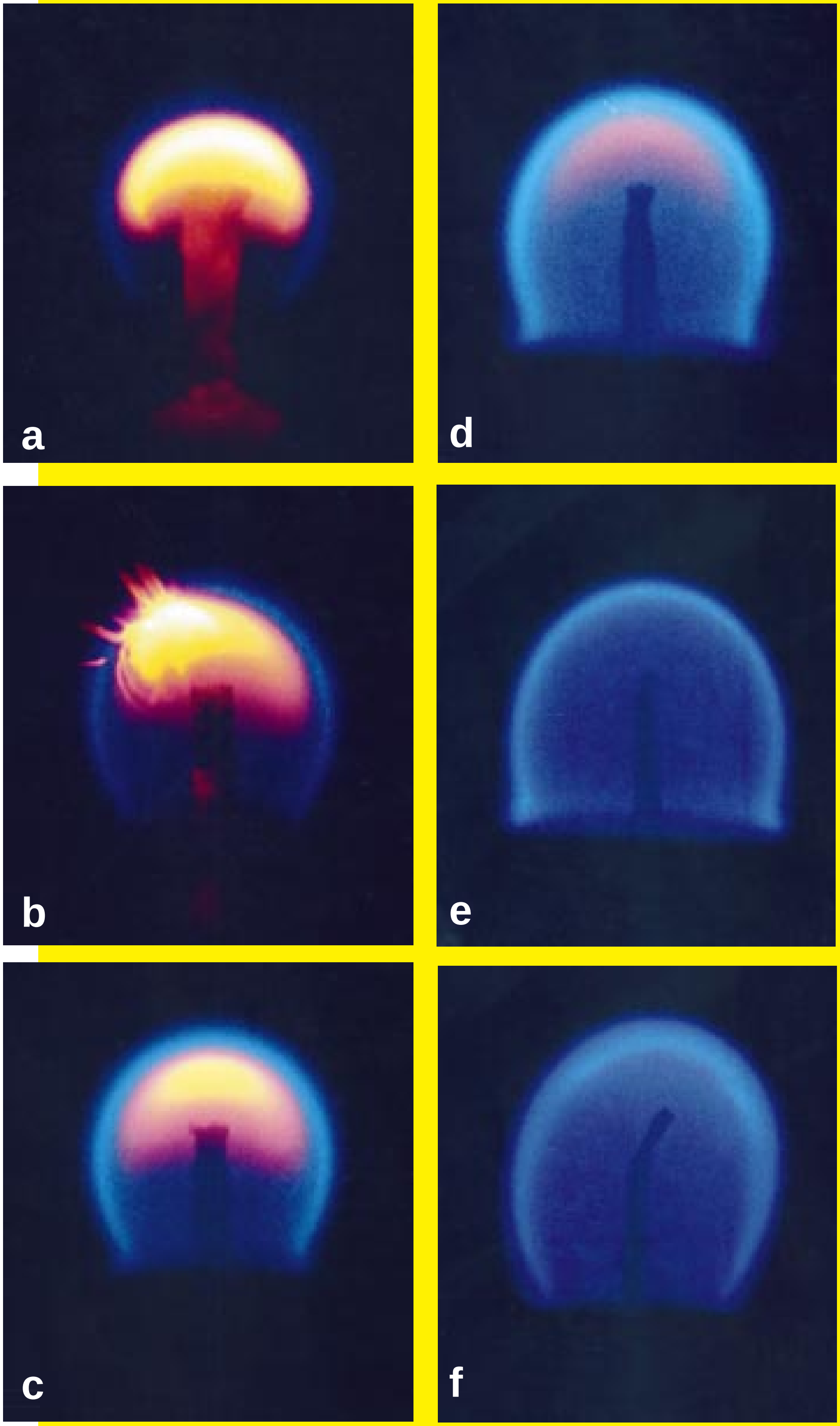
On the cover: On Earth, gravity-driven buoyant convection causes a candle flame to be teardrop-shaped (left photo) and carries soot to the flame's tip, making it yellow. In microgravity, where convective flows are absent, the flame is spherical, soot-free, and blue (right photo).

Why Conduct Combustion Science Research in Microgravity?

Research in microgravity permits a new range of combustion experiments in which gravity-driven forces such as buoyancy-induced flows and sedimentation are virtually eliminated. The effects of gravitational forces often impede combustion studies performed on Earth. For example, combustion generally produces hot gas (due to the energy released in the reaction), which is less dense than the cooler gases around it. In Earth's gravity (1 g), the hot gas is pushed up by the denser surrounding gases. As the hot gas rises, it creates movement — buoyancy-induced flow — that promotes the mixing of the unburned fuel, oxidizer, and combustion products.

The ability to significantly reduce gravity-driven flows in microgravity helps scientists in several ways. One advantage is that the "quieter" and more symmetric microgravity environment makes the experiments easier to model, thus providing a better arena for testing theories. In addition, eliminating buoyancy-induced flows allows scientists to study phenomena that are obscured by the effects of gravity, such as the underlying mechanisms of fuel and heat transport during combustion processes.

Sedimentation, another gravity-driven phenomenon, occurs when materials of unequal densities separate into distinct layers. The most dense materials settle at the bottom and the least dense rise to the top. Scientists often desire an even mixture of the component parts of fuels so that models developed from their experiments can use simplified equation sets to represent the processes that occur. Sedimentation affects combustion experiments involving particles or droplets because, as the components of greater density sink in a gas or liquid, their movement relative to the other particles creates an asymmetrical flow around the dropping particles. This can complicate the interpretation of experimental results. On Earth, scientists must resort to mechanical supports, levitators, and stirring devices to keep fuels mixed, while fluids in microgravity stay more evenly mixed without sticking together, colliding, or dispersing unevenly. Because buoyancy effects are nearly eliminated in microgravity, experiments of longer duration and larger scale are possible,



Candle Flames in Microgravity

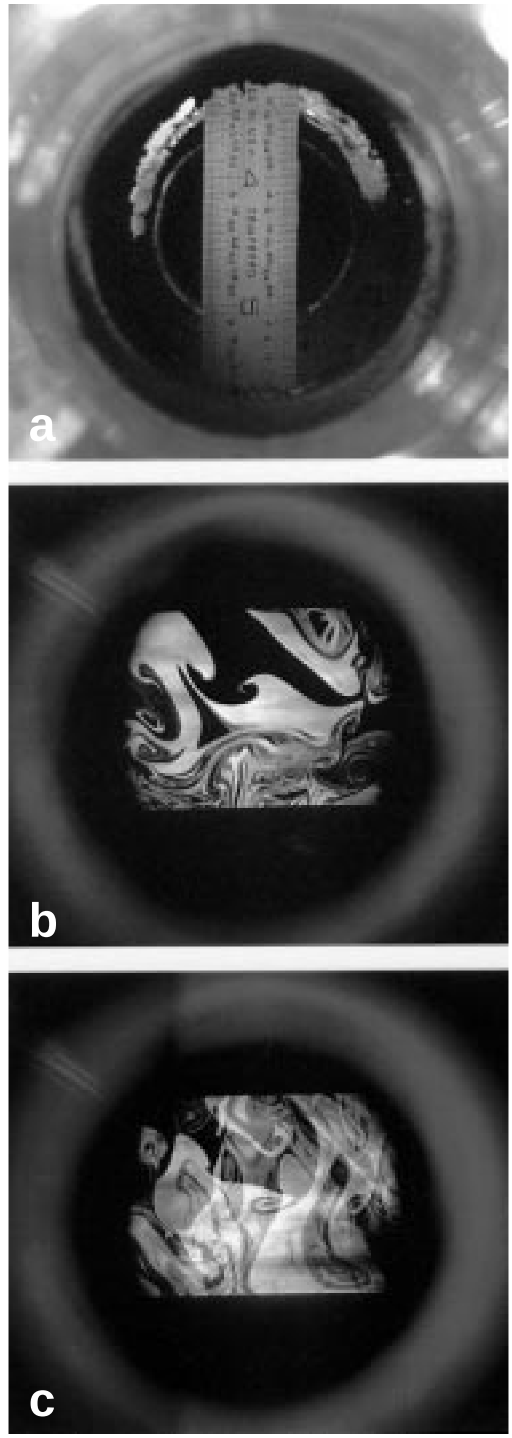
Candle flames behave differently in microgravity than they do on Earth. The primary reason for this difference is that microgravity provides an environment that lacks buoyant convection, which normally plays an important role in maintaining and shaping a flame on Earth. In Earth's gravity, buoyant convection develops when hot, less dense combustion products rise. The flow that results draws cooler surrounding air to the base of the flame, supplying it with the oxidizer (in this case, oxygen) that the flame requires to maintain itself. Combustion products (carbon dioxide, water vapor, and soot) are carried away from the flame by the same convective flow, which is the dominant transport mechanism in the flame. In microgravity, however, the process is not the same; there is no buoyant convection, and the transport of combustion products and oxygen occurs by the much slower process of molecular diffusion. This diffusion occurs when there is a high concentration of combustion products and a low concentration of oxygen close to the flame and a high concentration of oxygen farther away from the flame. The combustion products migrate away from the flame and the oxygen migrates toward the flame. The diffusive transport rates in microgravity are much lower than the transport rates due to natural convection in Earth's gravity. As a result, the flame will often appear to burn less vigorously than a flame on Earth, and it will assume a spherical shape that diffuses equally in all directions, rather than the more elongated shape that is characteristic of flames in Earth's gravity. Initial results from the Candle Flames in Microgravity (CFM) experiment, conducted on the Russian space station, Mir, *in 1996, showed that flames could survive over long periods of time in microgravity (in some cases over 45 minutes) and showed evidence of spontaneous and prolonged flame oscillations near extinction.*

This series of photographs from CFM shows a candle flame burning over time in microgravity. Photo **a** *shows the flame a few seconds after ignition. Photo* **b** *shows pieces of wax or soot moving through the flame about 25 seconds after ignition. Photo* **c** *shows that the candle continues to exhibit soot (which burns yellow and orange in flame) 45 seconds after ignition. Photo* **d***, taken 65 seconds after ignition, shows that the flame grows in size and exhibits less soot. Photo* **e** *shows that the candle flame continues to grow and burns soot-free (all blue flame) 95 seconds after ignition. Photo* **f** *shows that the candle flame continues to grow and burns soot-free 125 seconds after ignition. The flame extinguished approximately 3 minutes after ignition.*

and more detailed observation and examination of important combustion processes can occur.

To date, combustion science researchers have demonstrated major differences in the structures of various types of flames under microgravity conditions and under 1 g conditions. In addition to the practical implications of these results in combustion efficiency, pollutant control, and flammability, these studies establish that better mechanistic understanding of the individual processes involved in the overall combustion process can be obtained by comparing results obtained in microgravity to normal-gravity test results. One clear example of the advantage of these comparison tests is in the area of fire safety. Most smoke detectors have been designed to detect soot particles in the air, but the sizes of soot particles produced in 1 g are different from those produced in microgravity environments. This means that smoke-detecting equipment must be redesigned for use on spacecraft to ensure the safety of equipment and crew. Flame spread across surfaces is also quite different in microgravity.

Comparisons of research in microgravity and in 1 g have also led to improvements in combustion technology on Earth that may reduce pollutants and improve fuel efficiency. Technological advances include a spectroscopy system that measures the composition of gas emissions from factory smoke stacks so that they can be monitored. In addition, a monitor for ammonia, which is one gas that poses dangers to air quality, is already being produced and is available for industrial use. Engineers have also designed a fuel-lean flame stabilizer device that allows natural gas appliances to operate more efficiently while simultaneously reducing air pollution. This stabilizer may be used in home furnaces, industrial processing furnaces, and water heaters in the future. Another new technology is the use of advanced optical diagnostics and lasers to better define the processes of soot formation so that soot-control strategies can be developed. Devices have also been developed to measure percentages of soot in exhausts from all types of engines and combustors, including those in automobiles and airplanes.



These photos were taken during a ground-based experiment to test laser-induced incandescence, a new technique for measuring soot concentration. A soot-containing exhaust stream was created in a chimney, and pulsed high-intensity laser light was used to reveal soot distribution. Photo **a** *shows a ruler, with scale in inches, inserted in the chimney. Photo* **b** *shows the soot in the exhaust stream illuminated by one laser pulse, and photo* **c** *shows the soot illuminated by two laser pulses. This technique has also been successfully tested in microgravity.*

Combustion Science Research Areas

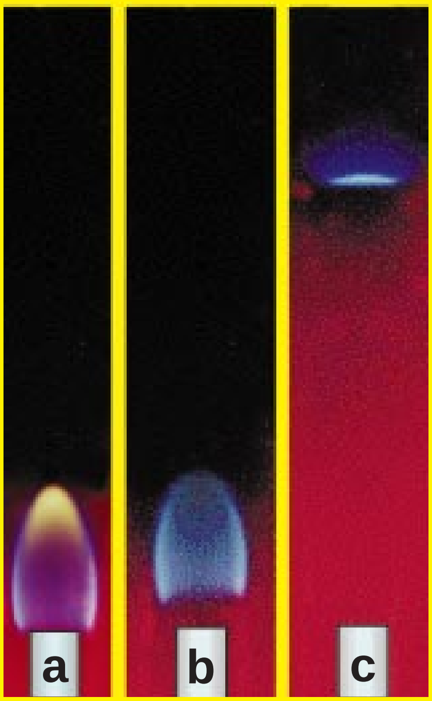
Premixed Gas Flames

In premixed gas flame research, the fuel and oxidizer gases are completely mixed prior to ignition. Scientists are interested in flame speed (the rate at which the flame zone travels away from the ignition source and into the unreacted mixture) as a function of both the type of fuel and oxidizer used and the oxidizer-to-fuel ratio. With sufficiently high or low ratios, the flame does not move into the unreacted mixture; these critical ratios are referred to as the upper and lower flammability limits and are of considerable interest in terms of both safety and fundamental science.

Gravity can strongly affect both flame speed and flammability limits, chiefly through buoyancy effects. Scientists in this area are also researching gravity's effects on the flame stability, extinction, structure, and shape of premixed gas flames.

Gaseous Diffusion Flames

Diffusion is a process through which molecules of one compound spread into the molecules of another, mixing on a molecular scale. In this area of research, the fuel and oxidizer gases are initially separate. They tend to diffuse into each other and will react at their interface upon ignition. The structure of these flames is quite different in the buoyancy-induced flows caused by Earth's gravity than in microgravity. Scientists study flame stability, burning rates, and diffusion flame structures, particularly their effect on soot formation. Within this area, results of studies of the behavior of gas-jet flames in a microgravity environment, both in transition and in turbulent flows, are being used to develop models with potential applications in creating effective strategies to control soot formation in burners that are used in many practical appliances.



Enclosed diffusion flames are commonly found in practical combustion systems, such as the power plant combustor, gas turbine combustor, and jet engine afterburner. In these systems, the fuel is injected into a duct with a co-flowing or cross-flowing airstream, and the diffusion flame is found at the surface where the fuel jet and oxygen meet, react, and consume each other. In combustors, this flame is anchored at the burner unless adverse conditions cause the flame to lift off. If the flame lifts off too far or too suddenly, it will blow out. This can cause fuel efficiency problems in combustors or safety problems in jet engines, in which re-light of the engine is often very difficult. The stability of these flames will be studied in microgravity because more controlled experiments, without the effects of buoyant convection confusing the effects of airflow, can be conducted. Comparison of the results of the Enclosed Laminar Flames microgravity experiment to 1 g studies will allow scientists to determine which effects result from buoyant convection and which result from airflow. The results of the experiment will also help scientists to learn more about flame stabilization in a co-flow environment.

The series of photos above was taken during a ground-based investigation of a methane-fueled laminar flame surrounded by co-flowing air. The flame was enclosed in a chamber, and the pressure reduced. As the pressure decreased, the velocity of the flow increased, causing the flame to change from a stabilized condition (photo **a***, taken at 0.49 atm and a flow velocity of 28 cm/sec), to lift-off (photo* **b***, taken at 0.29 atm and a flow velocity of 49 cm/sec), to near blow-out, or extinction (photo* **c***, taken at 0.22 atm and a flow velocity of 64 cm/sec).*

Liquid Fuel Droplets and Sprays

In this research area, scientists study the combustion of individual liquid fuel droplets suspended in an oxidizing gas (air, for example). For these experiments, investigators commonly use fuels such as heptane, kerosene, and methanol. Gravity hinders fundamental studies of droplet combustion on Earth due to flows induced by high-density droplets that sink and buoyancy-induced upward acceleration of hot combustion products relative to the surrounding gas. These flows cause drops to burn unevenly, making it difficult for scientists to draw conclusions from their experiments.

This area of study also includes the investigation of the combustion of sprays and ordered arrays of fuel droplets in a microgravity environment for an improved understanding of interactions between individual burning droplets in sprays. Knowledge of spray combustion processes resulting from these studies should lead to major improvements in the design of combustors utilizing liquid fuels.

Fuel Particles and Dust Clouds

This area is particularly important in terms of fire safety, since clouds of coal dust have the potential to cause mine explosions, and grain-dust clouds can cause silos and grain elevators to explode. It is particularly difficult to study the fundamental combustion characteristics of fuel-dust clouds under normal gravity because initially well-dispersed dust clouds quickly settle due to density differences between the particles and the surrounding gas. Because particles stick together and collide during the sedimentation process, they form nonuniform fuel-air ratios throughout the cloud. In microgravity, fuel-dust clouds remain evenly mixed, allowing scientists to study them with much greater experimental control. Their experimental results contribute to the goal of mitigating coal mine and grain elevator hazards.

Flame Spread Along Surfaces

An important factor in fire safety is inhibiting the spread of flames along both solid and liquid surfaces. Flame spread involves the reaction between an oxidizer gas and a condensed-phase fuel or the vapor produced by the "cooking" of such a fuel. Research has revealed major differences in ignition and flame-spreading characteristics of liquid and solid fuels under microgravity and normal-gravity conditions. Material flammability tests in 1 g, which are strongly affected by buoyancy-induced flows, do not match results obtained in microgravity. It is therefore useful to study both flame spread and material flammability characteristics in microgravity to ensure fire safety in environments with various levels of gravity.

The knowledge gained from these studies may also lead to better understanding of dangerous combustion reactions on Earth. Microgravity experiments eliminate complexities associated with buoyancy effects, providing a more fundamental scenario for the development of flame-spreading theories.

Smoldering Combustion

Smoldering combustion is a relatively slow, nonflaming combustion process involving an oxidizer gas and a porous solid fuel. Well-known examples of smoldering combustion are lit cigarettes and cigars. Smoldering combustion can also occur on much larger scales with fuels such as polyurethane foam. When a porous fuel smolders for a long period of time, it can create a large volume of gasified fuels, which are ready to react suddenly if a breeze or some other oxidizer flow occurs. This incites the fuel to make the transition to full-fledged combustion, often leading to disastrous fires (like those involving mattresses or sofa cushions). Since heat is generated slowly in this process, the rate of combustion is quite sensitive to heat exchange; therefore, buoyancy effects are particularly important. Accordingly, smoldering combustion is expected to behave quite differently in the absence of gravity.

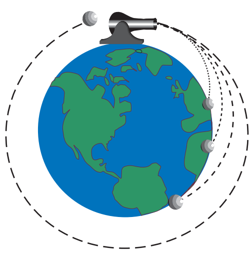
The Forced Flow Flame-Spreading Test was designed to study flame spreading over solid fuels when air is flowing at a low speed in the same direction as the flame spread. Previous research has shown that in low-speed concurrent airflows, some materials are more flammable in microgravity than on Earth. The top image shows a 1.5-cm flame in microgravity that melts a polyethylene cylinder (3 mm in diameter) into a liquid ball. Above the flame, a small particle of fuel is ejected from the liquid ball and catches fire. The bottom image shows a 10-cm flame in microgravity that burns almost entirely blue on both sides of a thin sheet of paper. The glowing thermocouple in the lower half of the flame provides temperature measurements. There is a slight airflow from right to left, in the same direction as the flame spread, in both photos.

Combustion Synthesis

Combustion synthesis, a relatively new area of research, involves creating new materials through a combustion process and is closely tied to work in materials science. One subcategory of particular interest is referred to as self-deflagrating high-temperature synthesis (SHS). SHS occurs when two materials — usually two solids — are mixed together, are reactive with one another, and create a reaction that is highly exothermic (gives off a large amount of heat). Once the reaction is started, the flame will propagate through a pressed mixture of these particles, resulting in a new material. Much of the initial research in this groundbreaking area involves variables such as composition, pressure, and preheat temperature. Manipulating these factors leads to interesting variations in the properties of materials created through the synthesis process.

Flame processes are also being used to create fullerenes and nanoparticles. Fullerenes, a new form of carbon, are expensive to produce at this point and cannot be produced in large quantities, but scientists predict more uses for them will be developed as they become more readily available. Initial indications are that some fullerene compounds may be used as superconductors. Nanoparticles (super-small particles) are also of great interest to materials scientists due to the changes in the microstructures of compacted materials that can be produced by sintering them, which results in improved properties of the final products. These nanoparticles can thus be used to form better pressed composite materials.

Gravity and Microgravity



In his "thought experiment," Isaac Newton hypothesized that by placing a cannon at the top of a very tall mountain and firing a cannonball at a high enough velocity, the cannonball could be made to orbit the Earth.

Gravity is such an accepted part of our lives that we rarely think about it, even though it affects everything we do. Any time we drop or throw something and watch it fall to the ground, we see gravity in action. Although gravity is a universal force, there are times when it is not desirable to conduct scientific research under its full influence. In these cases, scientists perform their experiments in microgravity — a condition in which the effects of gravity are greatly reduced, sometimes described as "weightlessness." This description brings to mind images of astronauts and objects floating around inside an orbiting spacecraft, seemingly free of Earth's gravitational field, but these images are misleading. The pull of Earth's gravity actually extends far into space. To reach a point where Earth's gravity is reduced to one-millionth of that on Earth's surface, one would have to be 6.37 million kilometers away from Earth (almost 17 times farther away than the Moon). Since spacecraft usually orbit only 200–450 kilometers above Earth's surface, there must be another explanation for the microgravity environment found aboard these vehicles.

Any object in freefall experiences microgravity conditions, which occur when the object falls toward the Earth with an acceleration equal to that due to gravity alone (approximately 9.8 meters per second squared [m/s^2], or 1 g at Earth's surface). Brief periods of microgravity can be achieved on Earth by dropping objects from tall structures. Longer periods are created through the use of airplanes, rockets, and spacecraft. The microgravity environment associated with the space shuttle is a result of the spacecraft being in orbit, which is a state of continuous freefall around the Earth. A circular orbit results when the centripetal acceleration of uniform circular motion ($\mathbf{v}^2/\mathbf{r}$; $\mathbf{v}$ = velocity of the object, $\mathbf{r}$ = distance from the center of the object to the center of the Earth) is the same as that due to gravity alone.

Microgravity Research Facilities

A microgravity environment provides a unique laboratory in which scientists can investigate the three fundamental states of matter: solid, liquid, and gas. Microgravity conditions allow scientists to observe and explore phenomena and processes that are normally masked by the effects of Earth's gravity.

NASA's Microgravity Research Division (MRD) supports both ground-based and flight experiments requiring microgravity conditions of varying duration and quality. These experiments are conducted in the following facilities:

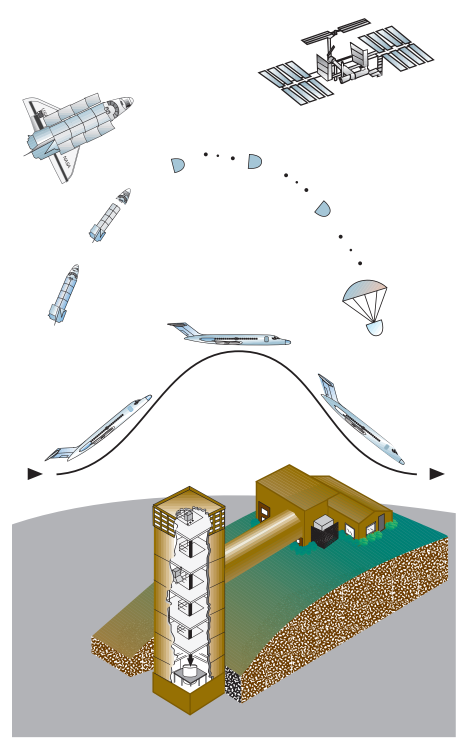
A **drop tower** is a long vertical shaft used for dropping experiment packages, enabling them to achieve microgravity through freefall. Various methods are used to minimize or compensate for air drag on the experiment packages as they fall. Lewis Research Center in Cleveland, Ohio, has two drop facilities (one 24 meters tall and one 132 meters deep) that can accommodate experiments which need only a limited amount of time (2.2 or 5.2 seconds) in microgravity or which are test runs of experiments that will later be performed for longer periods in an aircraft, rocket, or spacecraft.

Reduced-gravity aircraft are flown in parabolic arcs to achieve longer periods of microgravity. The airplane climbs rapidly until its nose is at an approximate 45-degree angle to the horizon. Then the engines are briefly cut back, the airplane slows, and the nose is pitched down to complete the parabola. As the plane traces the parabola, microgravity conditions are created for 20–25 seconds. As many as 40 parabolic trajectories may be performed on a typical flight.

Sounding rockets produce higher-quality microgravity conditions for longer periods of time than airplanes. An experiment is placed in a rocket and launched along a parabolic trajectory. Microgravity conditions are achieved during the several minutes when the experiment is in freefall prior to re-entering Earth's atmosphere.

A **space shuttle** is a reusable launch vehicle that can maintain a consistent orbit and provide up to 17 days of high-quality microgravity conditions. The shuttle, which can accommodate a wide range of experiment apparatus, provides a laboratory environment in which scientists can conduct long-term investigations.

A **space station** is a permanent facility that maintains a low Earth orbit for up to several decades. The facility enables scientists to conduct their experiments in microgravity over a period of several months without having to return the entire laboratory to Earth each time an experiment is completed.



Microgravity Research Division